

Using Multiwavelength Observations to Estimate the Black Hole Masses and Accretion Rates in Seyfert Galaxies

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Abstract.

We model the spectral energy distribution of the type 1 Seyfert galaxies, fitting data from simultaneous optical, UV, and X-ray monitoring observations. We assume a geometry consisting of a hot central Comptonizing region surrounded by a thin accretion disk. The properties of the disk and the hot central region are determined by the feedback occurring between the hot Comptonizing region and thermal reprocessing in the disk that, along with viscous dissipation, provides the seed photons for the Comptonization process. The constraints imposed upon this model by existing multiwavelength data allow us to derive limits on the central black hole mass, the accretion rate, and the radius of the transition region between the thin outer disk and the geometrically thick, hot inner region in these objects.

1. Introduction

In a series of three papers (Chiang & Blaes 2001, Chiang 2002, and Chiang & Blaes 2003), we showed that the optical/UV (OUV) and X-ray light curves obtained from multiwavelength monitoring campaigns of bright type 1 Seyfert galaxies could be readily explained by thermal reprocessing of radiation from a central X-ray source by a thin accretion disk. These observations had been puzzling since there is no apparent correlation between the OUV and X-ray light curves (Nandra et al. 1998; Edelson et al. 2000) as predicted by early models of thermal reprocessing (Krolik et al. 1991; Courvoisier & Clavel 1991; Collin-Souffrin 1991). The resolution of these difficulties were pointed to by Nandra et al. (2000) who noted that for the NGC 7469 observations the OUV variations *are* correlated with the X-ray spectral index as well as with an extrapolation of the measured 2–10 keV fluxes up to 100 keV. This latter result leads to the natural conclusion that the disk flux from thermal reprocessing is driven by the bolometric X-ray luminosity, which can differ substantially from that seen in narrow band observations (e.g., 2–10 keV) owing to variations in the X-ray spectral shape.

If the hard X-ray emission in type 1 Seyfert galaxies is produced by thermal Comptonization in a hot plasma, then the X-ray spectral index is determined by the plasma temperature and the optical depth to Compton scattering. Furthermore, if the thermal reprocessed emission comprises a significant fraction of the seed photons for the Comptonization process, then the feedback between the plasma and the reprocessing material acts as a thermostat, regulating the temperature of the plasma (Stern, et al. 1995). For a given optical depth, the spectral index of the emission is then set by the strength of the feedback, and that, in turn, is determined by the geometry of the hot plasma and the reprocessing material and by the amount of seed photons that are not due to reprocessing (Poutanen, Krolik, & Ryde 1997; Zdziarski, Lubiński, & Smith 1999).

2. The Model

There is an empirical relation between the Compton amplification factor, defined as the ratio of X-ray luminosity to seed photon luminosity entering the plasma, $A = L_x/L_s$, and the spectral index of the thermal Comptonization continuum:

$$\Gamma = \Gamma_0 \left(\frac{L_x}{L_s} - 1 \right)^{-1/\delta}. \quad (1)$$

Here, parameter values of $\Gamma_0 = 2.06$ and $\delta = 15.6$ have been found from fits to Monte Carlo calculations of the thermal Comptonization process (Chiang & Blaes 2003; see also Malzac, Beloborodov, & Poutanen 2001, and Beloborodov 1999). Thus, the amplification factor A is essentially determined for a given geometry and intrinsic seed photon distribution.¹

Since the shape of the OUV spectral energy distribution (SED) of type 1 Seyfert galaxies is roughly consistent with emission from a multitemperature thin disk, albeit with significant color corrections (Hubeny et al., 2001), and since the X-ray emitting region must have a fairly small size ($\lesssim 10^{14} \text{cm} \sim \mathcal{O}(10 GM/c^2)$) from variability time scales, we model the geometry of the inner regions of these objects as consisting of a hot, centrally-located spherical plasma with a razor thin accretion disk encircling it. Some adjustable overlap exists between the disk and the central plasma that allows for variation in the amplification factor, and thus, will also allow for spectral variation. This geometry is motivated by the disk instability models of Shapiro, Lightman & Eardley (1976) as well as by more recent advection-dominated accretion flow (ADAF) models (e.g., Narayan & Yi 1995). Following these models, we will assume that the central spherical plasma region is the disk accretion flow having made a transition from a relatively cold, standard thin disk to a geometrically thick, hot inner flow.

For observations of the Seyfert galaxies NGC 5548 (Magdziarz et al. 1998), NGC 7469 (Nandra et al. 1998), and NGC 3516 (Edelson et al. 2000), the combinations of ground-based optical spectra and UV spectroscopy from IUE and/or HST provide sufficient spectral coverage to determine shape of the OUV SED, including, crucially, the roll-over at the higher frequencies. In our simple

¹There is a slight complication in that the thermal Compton emission is not completely isotropic, being preferentially back-scattered for the lowest orders.

picture of the accretion disk, the emission at any given radius comprises thermal radiation from internal viscous dissipation and from thermal reprocessing. For our chosen “sphere + disk” geometry, both of these sources of emission obey a $\propto r^{-3/4}$ temperature distribution. Therefore, the inner truncation radius of the thin disk, r_{tr} , where it makes the transition to the geometrically thick, hot central plasma region, determines the shape of the OUV roll-over, while the temperature at this radius sets the magnitude of the OUV SED. Once the disk temperature is set by the OUV observations, the source of seed photons from both thermal reprocessing and viscous dissipation is fully determined.

The temperature of the Comptonizing electrons, the optical depth and the radius of the central plasma sphere can then be found by fitting the X-ray flux and spectral index. For a single epoch of data, this leaves one parameter of this model unconstrained. If one assumes a Thomson depth of unity, then the full SED from the optical through hard X-rays can be described with reasonable parameters (Chiang & Blaes 2001). We note that this model would be completely constrained if the high energy roll-over of the thermal Comptonization continuum could be reliably measured. Such measurements would provide direct estimates of both the temperature of the Comptonizing plasma and the overall bolometric luminosity. In analogy with Galactic low mass X-ray binaries, this roll-over is believed to occur at cut-off energies of ~ 100 keV. Unfortunately, there have not been any X-ray observing missions with the effective area required to measure the X-ray spectra at these energies on sufficiently short time scales.

Another constraint may be imposed that comes from the expectation that the hot central plasma must be less efficient at radiating accretion power than a standard optically thick disk would be in its place. This condition yields the relation

$$L_x < \eta \dot{M} c^2 - L_{\text{disk}}, \quad (2)$$

where $\eta \sim 0.1$ – 0.4 is the expected efficiency for a thin disk that extends all the way to the innermost stable circular orbit, \dot{M} is the accretion rate, and $L_{\text{disk}} = L_{\text{disk}}(M\dot{M})$ is the luminosity of the truncated disk from internal viscous dissipation. Although this condition adds a constraint it also adds yet another unknown quantity, the product $M\dot{M}$ (Chiang & Blaes 2003).

Multiwavelength observations of variability on time scales that are shorter than the expected viscous times for these systems ($t_{\text{visc}} > 10^8$ s) can provide additional information that can be used to estimate the above model parameters uniquely. On these time scales, for typical type 1 Seyfert galaxies, we can take $M\dot{M}$ to be constant. Since there is one fewer constraint than there are model parameters, we can solve for one of the model parameters as a function of another for any given set of OUV and X-ray observations. In figure 2 of Chiang & Blaes (2003), we plot the plasma electron temperature, $k_B T_e$, versus $M\dot{M}$ for each of nine epochs of the OUV/X-ray data available for NGC 5548 (Magdziarz et al. 1998; Chiang & Blaes 2003). Assuming that a single value of $M\dot{M}$ must obtain for all nine epochs, we can infer an upper limit based on the restriction that the electron temperature cannot be smaller than $\simeq 30$ keV, otherwise evidence of the thermal Comptonization cut-off would have been seen in the epoch 7 Ginga X-ray data. This constraint yields $M\dot{M} \lesssim 2.5 \times 10^5 M_\odot^2 \text{yr}^{-1}$. The dotted vertical lines indicate the black hole masses $M = (1, 2, 3, 4, 5, 6, 7) \times 10^7 M_\odot$ found for the epoch 1 data, which are the most constraining. Given that the

black hole mass must be considered constant as well, this yields an upper limit of $M \lesssim 2 \times 10^7 M_\odot$. By contrast, the mass measured for NGC 5548 using reverberation mapping is $M \simeq 6 \times 10^7 M_\odot$ (Peterson & Wandel 2000).

We have applied similar analyses to data for NGC 3516 and NGC 7469 (Chiang 2002). Although we could not estimate the disk inner truncation radius for NGC 3516 since the OUV data do not show a high frequency decline, we can use the observations of a broad Fe K α line to identify the inner truncation radius of the thin disk with the innermost stable circular orbit. From our analyses of the multiwavelength data, we find a black hole mass of $M \lesssim 2 \times 10^7 M_\odot$. For NGC 7469, we find $M\dot{M} \sim 10^6 M_\odot^2 \text{yr}^{-1}$; this agrees with a value found from a completely independent method that considers interband OUV continuum time lags under the assumption of thermal reprocessing by a thin disk (Collier et al. 1998). Reverberation mapping observations place the central black hole mass of NGC 7469 in the range $M \sim 10^6\text{--}10^7 M_\odot$. Along with our estimate of $r_{\text{tr}} \sim 3 \times 10^{14} \text{cm}$ for the thin disk inner truncation radius, this implies $r_{\text{tr}} \gtrsim 200 GM/c^2$ which is consistent with observations of a narrow, unresolved Fe K α line as seen by ASCA for this object (Guainazzi et al. 1994).

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